02/15/09
TD-09-007

LQ Protection Heater Test at Liquid Nitrogen Temperature

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Content:

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1. Introduction

The US LHC accelerator research program (LARP) is developing long Nb_3Sn coils for the LHC interaction region upgrade. The long quadrupole LQ-magnet is a ~ 3.5-m scale-up of the previously built and successfully tested short magnet prototypes (TQ). A major milestone for the LQ program will be the test at Fermilab in second half of 2009.

A novel heater configuration has been designed for LQ magnets in order to provide both maximum coverage and redundancy, and without using the copper shunting. Heaters are implemented on flexible circuits which are potted with the inner and the outer coil layers [1]. Comprehensive heater study was performed previously for the short magnet prototypes of the TQ series [2], [3]. The new design of LQ heaters, as well as heater application on both the inner and outer coil surfaces suggested performing an LQ protection heater test.

LQ practice coil # 5 equipped with all protection heaters was used for the heater test described in this note. Test at a liquid nitrogen temperature was performed in the Fermilab Technical Division on December 30-31st 2008.

2. LQ Protection Heater Design

LQ protection heaters are made of stainless steel strip. Each coil layer has two 1.7-m long traces. As described in Fig.1, the stainless steel strip becomes narrow locally in order to increase the resistance and create the so-called heating stations equidistantly distributed longitudinally along the coil. Between two heating stations, the stainless steel strip becomes wider, reducing the heater resistance and providing less Joule heating. Therefore the quenching of the underlying coil area depends on the propagation velocity of the quench generated by the heating stations. The width of the wide part of the strip is 23 mm. The width of the heating element is 9 mm, allowing the coverage of 4 strands in the coil.

The resistance of each heater is of the order of 7 Ω with a resistance of ~ 0.1 Ω for the heating stations. With a maximum voltage of 450 V across the heater, the maximum current that the heater can carry is equal to 64 A, leading to a power density in the heating element of the order of 150 W/cm^2. Power density as a function of the heater current is shown in Fig. 2.

Heaters on the same inner or outer layer of different coils will be connected in parallel to the single Heater Firing Unit (HFU). In total 4 HFUs will be used for all 16 protection heaters in LQ quadrupole. Polarity of power connection to LQ heaters are shown in Fig. 3.

When 4 protection heaters are connected in parallel, the equivalent resistance of the HFU circuit including all wires will reach ~ 2 Ohms. Therefore with the maximum HFU bank voltage of 450 V one should expect 225 A current in the circuit, which will exceed the HFU limit for a peak current of 200 A. Study of ratings and characteristics of the

HFU components showed that HFU can withstand much higher currents up to 800 A but for a short pulse-train duration less than 100 ms. Time constant (RC) for LQ heater discharge should not exceed 40 ms during the normal operation when 4 heaters are connected in parallel. Time constant will stay below 100 ms even if 2 out of 4-heaters connected in parallel will fail (become open). It was an additional motivation for this test to check HFU performance at currents above 200 A.

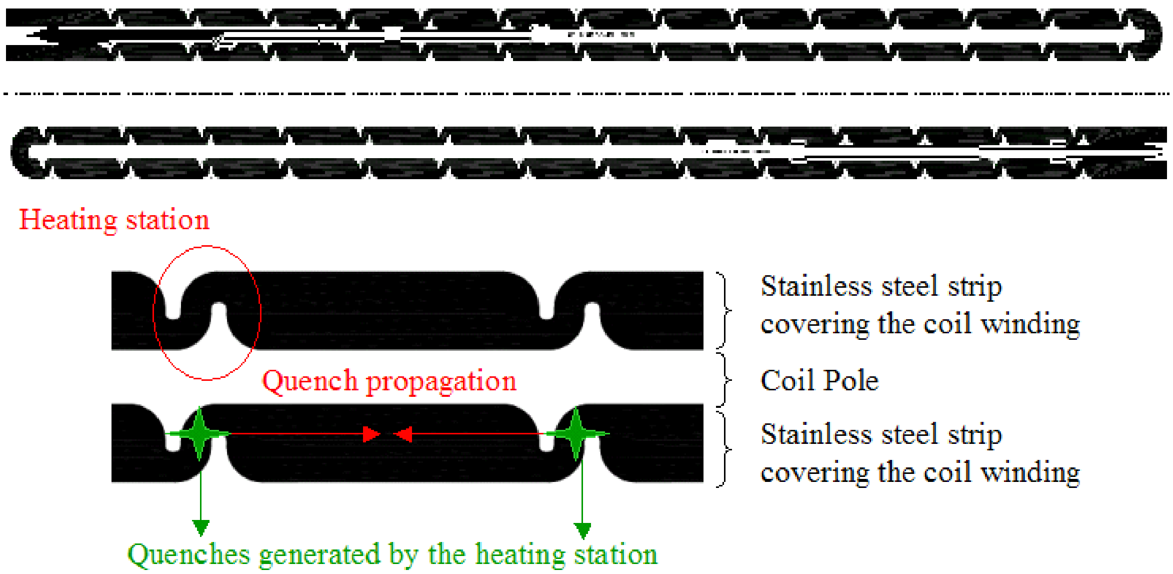

Fig. 1. Inner layer heaters and voltage taps trace (top). Protection heater schematic: the 100% coverage is achieved by the heating stations and the quench propagation velocity (bottom).

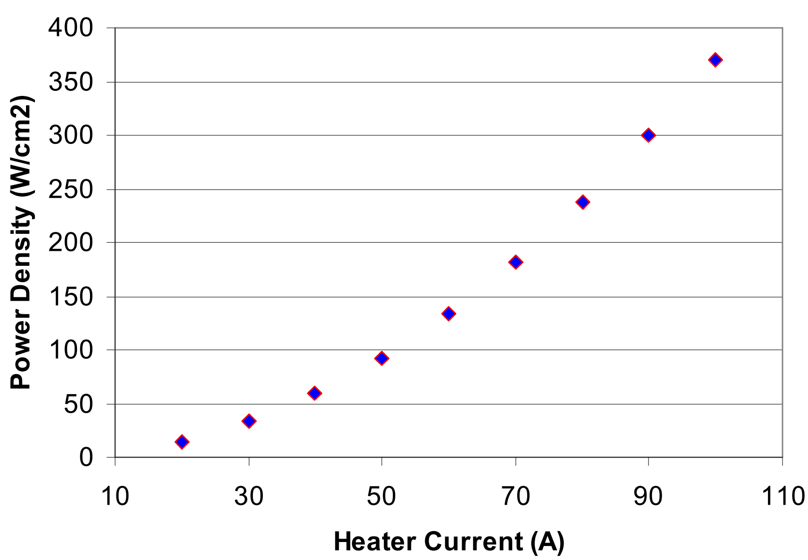

Fig. 2. Power density in heating stations as a function of the heater current

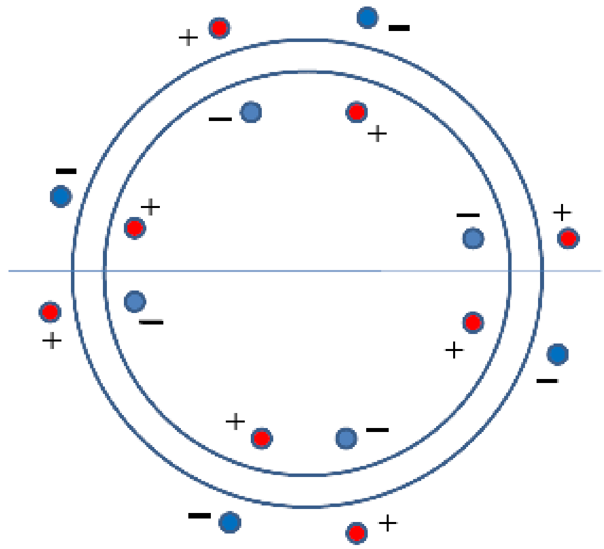

Fig. 3. Polarity of power connection to LQ protection heaters

2. Test Setup

Heater test was performed in high bay area of the Technical division IB3 building. LQ practice coil # 5 with protection heaters on both inner and outer coil layers was used for this test. For simplicity test was performed only at a liquid nitrogen temperature and without DAQ system. Coil was immersed in a wood box with the dimensions of 6"x6"x200". The box was filled with liquid nitrogen until it fully covered the coil. For the vessel insulation we used two 5-mil Kapton sheets and several layers of polyurethane sheet. Wood vessel for the heater test is shown in Fig. 4. Two nitrogen containers (100 G) were used during the 2-day test.

Coil #5 heaters were connected to a single module HFU through the heater distribution box, which allowed changing connection scheme during the test. 18-gauge wires were used for powering the heaters. Resistance measurements were done using a "Agilent" 34401A digital multi-meter. Heater firing unit and heater distribution box are shown in Fig. 5.

3. Heater Test

LQ heaters on coil #5 were tested for 2 different connection schemes: a single heater strip connected to the HFU or a set of 4 heaters connected in parallel to the HFU. Single unit HFU bank capacitance varies between 2.4 mF, 4.8 mF, 9.6 mF, 19.2 mF and voltage may reach 450 V. When firing under certain currents the protection heaters could develop a heat enough to reach room temperature according to our preliminary estimations. One of the main goals for this test was to verify that there is enough margin for heater firing under conditions close and slightly exceeding the operation limits. Detailed run plan for the LQ protection heater test is presented in Appendix I.

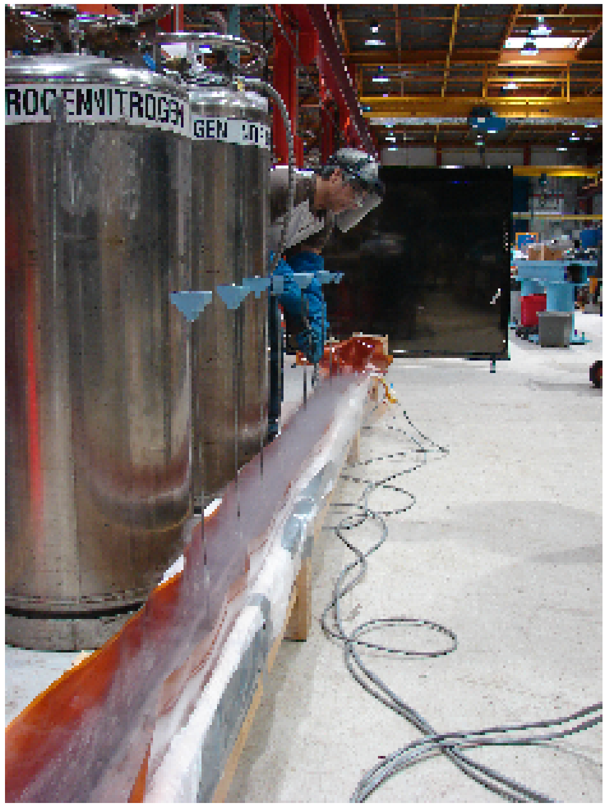

Fig. 4 Coil #5 immersed in a wood box with liquid nitrogen

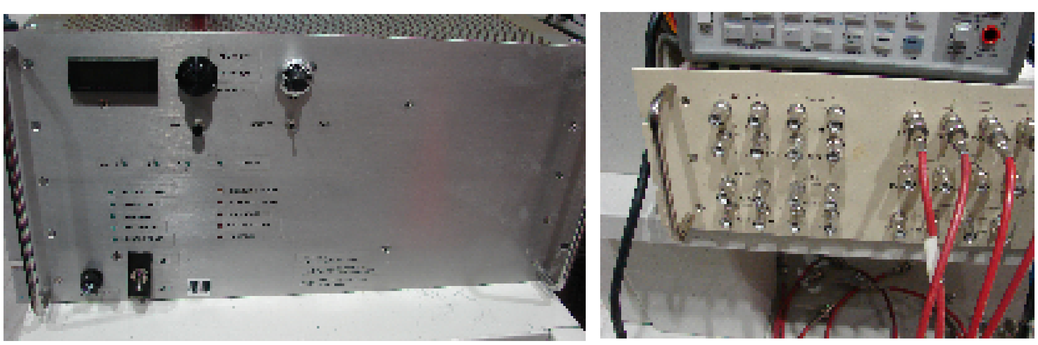

Fig. 5. Heater firing unit (left) and distribution box (right) used for the LQ heater test. Heaters were powered through 18-gauge wires.

Heater to coil hipot at 1000 V was performed before the test at 300 K and at ~ 77 K when coil was immersed in a liquid nitrogen bath. In the course of the test, as well as after the test, heater to coil hipot served as a most reliable test for the heater condition. The leak current never exceeded 0.02 μA. In addition, after each heater firing we measured the heater resistance for a fast diagnosis of possible problems.

Heater resistances at a room temperature and at 77 K are presented in Table 1. These 4-wire measurements (2-wire in case of 77 K measurements) are combined heater and wire resistances.

Table 1. Combined heater and wire resistances at 300 K and 77 K temperatures

Heater Resistance	LE Inner	LE Outer	RE Inner	RE Outer
at 300 K (4-wire), Ohm	6.81	6.58	6.79	6.89
at 77 K (2-wire), Ohm	5.1	4.95	5.09	5.22

During the test LQ protection heaters performed properly, exhibiting most intense nitrogen boiling in areas around the heating stations, as expected (see Fig. 6).

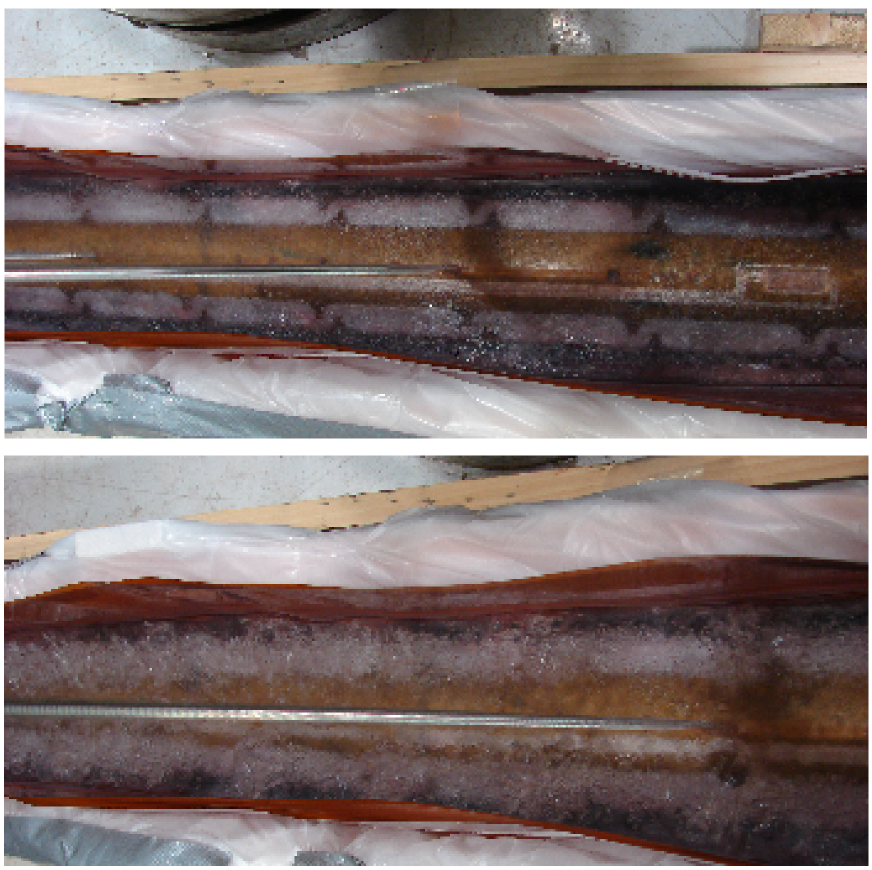

Fig. 6. LQ coil #5 in a liquid nitrogen bath before (top) and after (bottom) firing of the protection heaters.

3.1 Testing Single Protection Heaters

In this test each protection heater was fired at a HFU voltage and capacitance not exceeding the expected operational values. The HFU capacitance was set to 4.8 mF and voltage varied from 200 V to 400 V. The current in heaters was within 35-55 A for a time constant of 16-27 ms. Heater resistance was measured after every HFU firing and heater to coil hipot was performed after all 4 protection heaters were tested. Hipot results were consistent with one obtained before the test.

3.2 Testing 4 Protection Heaters Connected in Parallel

It was already mentioned in Section 2 that for LQ magnet protection 4 heaters on the same layer of different coils will be connected in parallel to each HFU. Goal of this test was to fire heaters under conditions below and close to the operational settings, in order to check the HFU performance.

The measured (2-wire) equivalent resistance was 1.4 Ohm. Heaters were fired at a HFU capacitance of 4.8 mF, 9.6 mF or 19.2 mF and at voltages 200 V, 300 V and 400 V. To ensure that test was successful we measured the equivalent resistance of heaters connected in parallel after each firing. Heater to coil hipot was not done since heater load, as well as the HFU load did not exceed one seen in previous test.

3.3 Single Protection Heater Test at High Currents

This test served as a stress test for each individual protection heater since the circuit current and time constant according to our calculations should increase temperature of the protection heater above room temperature (300 K). Both protection heaters at the magnet lead end were separately tested in this phase.

The HFU bank voltage was increased up to 450 V, and the HFU bank capacitance varied from 4.8 mF to 9.6 mF. Heater to coil hipot was done after each heater test.

In addition, each heater was fired 4-5 consecutive times at a HFU voltage of 400 V. The test was successful, without any problems during the hipot or resistance measurements.

3.4 HFU stress test

Main goal of this test was to see if the HFU survives the currents above the design limit (200 A). Protection heaters were connected in parallel and the HFU voltage was increased up to 450 V leading to current in HFU circuit at the level of ~ 300 A. At a HFU capacitance of 19.2 mF a time constant (RC) was ~ 28 ms.

No problems were encountered during this test as well.

4. Test Summary

Protection heaters of LQ practice coil #5 were tested at a liquid nitrogen temperature. Individual heaters or all 4 heaters connected in parallel were fired at different HFU voltages and capacitances. Some of the tests were performed at conditions close or beyond the operating limits for both the heaters and the HFU. Heater resistance was measured after each firing and heater to coil hipot was performed several times during the test when heater load was high. Heater to coil hipot was performed at 1000 V and the leak current never exceeded 0.02 μA.

All protection heaters were successfully tested and no difference was observed in performance of the heaters on the inner and outer coil layers. HFU also successfully survived currents in the circuit above 300 A for a short pulses up to 28 ms.

Even though one can expect different heat transfer at 77 K and 4.5 K, all test goals were achieved: the LQ heaters are working properly. Visual inspection of the magnet after the test confirmed that all protection heaters successfully passed the test.

A coil deflection of ~ 0.75 mm (difference in magnet height at the ends and the center) was measured immediately after removing the coil from the liquid nitrogen bath.

References

1. G. Ambrosio et al., "Long Quadrupole Design Report", LARP note, v.18, 2008
2. G.Chlachidze et al., "LARP TQC02b Magnet Test Summary", TD-08-026, 2008
3. G.Ambrosio et al., "LARP TQS02b Test Summary", TD-07-022, 2007

Appendix I:

Run plan

Room temperature preparation:

- Heater to coil Hipot, max. voltage 1000 V.
- Check strip heater resistance values at a room temperature

Test in the liquid nitrogen bath:

1. Check strip heater resistance values
2. "Cold" Heater to coil Hipot, max. voltage 1000 V.
3. Set HFU in a local mode and with initial settings for voltage and capacitance: 200 V and 4.8 mF
4. **Test individual heaters (4 in total on the inner and outer coil layers)**
    a. Connect individual strip heater to HFU and fire it

   b. Measure heater resistance after every test
   c. Repeat steps 3.a,b above for the HFU at 400 V and 4.8 mF
   d. Heater to coil Hipot after the test for each individual heater is completed
   e. *Expected current range in the HFU circuit is 35-55 A for a time constant of 16-27 ms*

5. **Test 4 heaters connected in parallel**
   a. Set HFU voltage at 200 V and capacitance at 4.8 mF
   b. Check a combined resistance of heaters connected in parallel
   c. Connect all heaters in parallel to HFU and fire it
   d. Measure heater resistance and check HFU after every test
   e. Repeat steps 4.b-d for HFU voltages 300 V, 400 V
   f. Repeat steps 4.b-e for HFU capacitance 9.6 mF and 19.2 mF
   g. *Expected current range in the HFU circuit is 100-210 A for a time constant of 9-36 ms*
6. **Test individual heaters at high currents**
   a. Connect strip heater at the outer layer LE to HFU
   b. Set HFU voltage 400 V and capacitance 4.8 mF
   c. Fire HFU and check heater resistance
   d. Repeat steps 5.a-c 4-5 times
   e. Heater to coil Hipot
   f. Repeat steps 5.a-c for the HFU at 425 V and 450 V
   g. Repeat steps 5.a-g for the inner layer LE strip heater
   h. Heater to coil Hipot after the test at each voltage is completed
   i. Repeat steps 5.a-h for the HFU capacitance of 9.6 mF
   j. Heater to coil Hipot after the test at each voltage is completed
7. **Test 4 heaters connected in parallel**
   a. Set HFU voltage at 425 V and capacitance at 19.2 mF
   b. Check a combined resistance of heaters connected in parallel
   c. Connect all heaters in parallel to HFU and fire it
   d. Measure heater resistance and check HFU after every test
   e. Heater to coil Hipot
   f. Repeat steps 6.a-e for HFU voltage at 450 V

Final room temperature checkout:

- Heater to coil Hipot, max. voltage 1000 V.
- Check strip heater resistance values at a room temperature